Dissertation Defense:
“$^{129}$Xe Relaxation and Rabi Oscillations”

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Oct. 30$^{\text{th}}$, 2013
Magnetic Resonance (MR)

- Energy difference (Zeeman) is “resonated” by applying an oscillating field

\[ \mu_S = \gamma S / \hbar \]

\[ -\mu_S \cdot B \rightarrow E \]

\[ E_{\downarrow} - E_{\uparrow} = \hbar \omega_0 \]
Magnetic Resonance (MR)

For most MR exp., an oscillating field is perpendicular to a larger, quantizing field.
Magnetic Resonance (MR)

- The linear $B'_1$ field can be decomposed as two counter-rotating components

\[ B'_1 = 2B_1 \]

\[ \text{Time} (t) \]
Magnetic Resonance (MR)

- In the high-field regime ($B_0 >> B_1$), use a rotating-wave approximation (RWA)

\[ B'_1 = 2B_1 \]
Magnetic Resonance (MR)

- The magnetic fields and spin state can be visualized using a Bloch-sphere picture.
Magnetic Resonance (MR)

- Considering a rotating-frame Bloch sphere (RFBS) elucidates spin dynamics.
In this way, the dynamics are also well visualized for a non-resonant pulse.
Magnetic Resonance (MR)

- This nutation about $B_{\text{eff}}$ is well-described quantitatively in a Rabi oscillation

\[
\Omega = \gamma B_1
\]
\[
\Omega_R = \sqrt{\Omega^2 + (\omega - \omega_0)^2}
\]

\[= \gamma B_{\text{eff}}\]
Nuclear MR (NMR)

- NMR samples have many spins, thermally polarized, totaling a net magnetization $\mathbf{M}$.

$$P_0 = P_\uparrow - P_\downarrow$$

$B_0$
Nuclear MR (NMR)

- $M$ is (conventionally) a pseudo-pure spin state, and only mimics a single spin state
However, as a proper sum of its spin constituents, $M$ obeys the same dynamics

$$P_\downarrow = \frac{\Omega^2}{\Omega_R^2} \sin^2 \left( \frac{\Omega_R t}{2} \right)$$
A typical, pulsed-NMR experiment relies on the function of a single coil.
Nuclear MR (NMR)

- The coil is first pulsed at the resonance frequency, causing a Rabi oscillation of $M$.

Result of a $90^\circ$, or $\pi/2$, flip angle.
- \( \mathbf{M} \) is torqued about \( B_0 \), inducing an EMF, and generates a free induction decay (FID).
Nuclear MR (NMR)

- Decay results from dephasing of spins due to local environment (local field)

(Spread in local $B_0$)
Nuclear MR (NMR)

- The decay results from dephasing of spins due to local environment (local field)
For some systems, the FID can be described by the characteristic relaxation time $T_2$.
A Fourier transform (FFT) of the FID gives a mapping to local field distributions.
After dephasing, spins return to thermal equilibrium with characteristic time $T_1$.

$1 - e^{-t/T_1}$

Time ($t$)
Hyperpolarization

- Spin-exchange optical pumping (SEOP) increases nuclear polarization by five orders of magnitude.
Hyperpolarization

- This boost in signal allows for $T_1$ experiments to be run from the ‘top down’
Optically pumped alkali metal vapor approaches 100% atomic polarization

**Optical Pumping**

- Ignoring Hyperfine

  - $5^2P_{1/2}$
  - $5^2S_{1/2}$
  - $m_J = -1/2, +1/2$

  - Average # of photons: 3/2

- With buffer gas (N$_2$)

  - $5^2P_{1/2}$
  - $5^2S_{1/2}$
  - $m_J = -1/2, +1/2$

  - Average # of photons: 1
Optical Pumping

- Calculate single photons being absorbed by an atom, in various conditions

\[ 87\text{Rb, } I = \frac{3}{2} \text{ Average # of photons: } 41.66 \]

\[ 85\text{Rb, } I = \frac{5}{2} \text{ Average # of photons: } 115.4 \]

\[ F = I + J \]
SEOP

- A highly polarized atomic spin-bath contacts with a nuclear spin-bath

\[ H = A I \cdot S + \gamma S \cdot N + \alpha K \cdot S \]
$T_1$ : Solid $^{129}$Xe Relaxation
Methods: Solid $^{129}$Xe Relaxation
Methods: Solid $^{129}$Xe Relaxation
Methods: Solid $^{129}$Xe Relaxation

− Trickle-freeze hyperpolarized xenon into sample chamber (Snow) held at 2 Tesla

− Set temperature of sample and perform $T_1$ experiment, with extremely small flip angles (approx. 1-8°)
Methods: Solid $^{129}$Xe Relaxation

- Able to take snow through liquid phase, and refreeze at 77 K (Ice)
Results: Solid $^{129}$Xe Relaxation

- See a substantial difference between ice and snow relaxation times at 77 K

![Graph showing comparison between ice and snow relaxation times with data points and fitted lines. The graph includes the following labels:
- Ice $T_1 = 169.7 \pm 0.6$ min.
- Snow $T_1 = 145.4 \pm 0.4$ min.
]
## Results: Solid $^{129}$Xe Relaxation

- Difference is reproducible across many set-ups

<table>
<thead>
<tr>
<th></th>
<th>$T_1$ (min.)</th>
<th>Probe</th>
<th>Flip Angle</th>
<th>Buffer Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>169.93 ± 0.25</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>168.16 ± 0.16</td>
<td>Tank</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>165.14 ± 0.70</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>168.7 ± 1.0</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>173.6 ± 1.5</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>171.44 ± 0.32</td>
<td>Flat</td>
<td>2.67° ± 0.19°</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>172.02 ± 0.31</td>
<td>Flat</td>
<td>3.11° ± 0.30°</td>
<td>No</td>
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<tr>
<td></td>
<td>166.55 ± 0.81</td>
<td>Flat</td>
<td>3.02° ± 0.07°</td>
<td>No</td>
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<tr>
<td></td>
<td>167.30 ± 0.33</td>
<td>Flat</td>
<td>3.31° ± 0.32°</td>
<td>Yes</td>
</tr>
<tr>
<td>Ice Average</td>
<td>169.2 ± 1.2</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

77 K

<table>
<thead>
<tr>
<th></th>
<th>$T_1$ (min.)</th>
<th>Probe</th>
<th>Flip Angle</th>
<th>Buffer Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>150.79 ± 0.43</td>
<td>Tank</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>148.47 ± 0.28</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>150.80 ± 0.25</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>148.61 ± 0.42</td>
<td>Tank</td>
<td>N/A</td>
<td>Yes</td>
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<tr>
<td></td>
<td>149.30 ± 0.40</td>
<td>Flat</td>
<td>8.96° ± 0.05°</td>
<td>No</td>
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<tr>
<td></td>
<td>149.80 ± 0.40</td>
<td>Flat</td>
<td>6.27° ± 0.07°</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>150.19 ± 0.37</td>
<td>Flat</td>
<td>6.91° ± 0.14°</td>
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<tr>
<td></td>
<td>151.02 ± 0.51</td>
<td>Flat</td>
<td>4.67° ± 0.22°</td>
<td>No</td>
</tr>
<tr>
<td>Snow Average</td>
<td>149.87 ± 0.54</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results: Solid $^{129}\text{Xe}$ Relaxation

Snow-oxygen introduction at 77 K

Oxygen-induced surface relaxation

$T_1 = 155.6 \pm 1.0$ min.

Oxygen causes exterior relaxation of crystallites.

Introduced additional oxygen at 175 min.

$T_1 = 156.9 \pm 1.5$ min.
Results: Solid $^{129}$Xe Relaxation

- Intrinsic difference in $^{129}$Xe $T_1$ between bulk snow and ice

- Theory predicts no difference between polycrystalline and single crystal $^{129}$Xe $T_1$

- Initial results at 77 K indicate ice $T_1$ is longer than theory suggests
Results: Solid $^{129}$Xe Relaxation

Ice

<table>
<thead>
<tr>
<th>Temp.</th>
<th>Fit $T_1$ (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>105 K</td>
<td>$100.4 \pm 0.4$</td>
</tr>
<tr>
<td>105 K</td>
<td>$98.1 \pm 0.3$</td>
</tr>
<tr>
<td>110 K</td>
<td>$98.9 \pm 0.7$</td>
</tr>
<tr>
<td>110 K</td>
<td>$93.6 \pm 0.6$</td>
</tr>
<tr>
<td>115 K</td>
<td>$85.8 \pm 0.5$</td>
</tr>
<tr>
<td>115 K</td>
<td>$85.0 \pm 0.3$</td>
</tr>
<tr>
<td>120 K</td>
<td>$75.6 \pm 0.3$</td>
</tr>
<tr>
<td>120 K</td>
<td>$76.7 \pm 0.2$</td>
</tr>
<tr>
<td>125 K</td>
<td>$73.2 \pm 0.2$</td>
</tr>
<tr>
<td>125 K</td>
<td>$70.8 \pm 0.3$</td>
</tr>
<tr>
<td>130 K</td>
<td>$64.1 \pm 0.2$</td>
</tr>
<tr>
<td>130 K</td>
<td>$68.8 \pm 0.2$</td>
</tr>
<tr>
<td>135 K</td>
<td>$63.7 \pm 0.1$</td>
</tr>
<tr>
<td>135 K</td>
<td>$62.9 \pm 0.2$</td>
</tr>
<tr>
<td>140 K</td>
<td>$60.9 \pm 0.4$</td>
</tr>
<tr>
<td>140 K</td>
<td>$59.7 \pm 0.2$</td>
</tr>
<tr>
<td>145 K</td>
<td>$63.6 \pm 0.1$</td>
</tr>
<tr>
<td>145 K</td>
<td>$55.1 \pm 0.2$</td>
</tr>
<tr>
<td>150 K</td>
<td>$51.8 \pm 0.2$</td>
</tr>
<tr>
<td>150 K</td>
<td>$50.4 \pm 0.1$</td>
</tr>
<tr>
<td>155 K</td>
<td>$44.2 \pm 0.3$</td>
</tr>
</tbody>
</table>
Results: Solid $^{129}\text{Xe}$ Relaxation

Ice

Low-temperature diverges from theory
Theory: Solid $^{129}\text{Xe}$ Relaxation

- Spin-rotation is dominate gas mechanism

$^{129}\text{Xe-Xe}$
Spin-rotation is dominate gas mechanism

THEORY OF QUADRUPOLAR NUCLEAR SPIN-LATTICE RELAXATION

by J. VAN KRANENDONK
Theory: Solid $^{129}$Xe Relaxation

- Van Kranendonk, Walker, PRL, (1967)
Theory: Solid $^{129}$Xe Relaxation

- Direct Process (DP)
  - Linear temp. dependence,
  - Field dependent

- Harmonic Raman (1R)
  - Quad. temp. dependence,
  - Field independent

- Anharmonic Raman (aR)
  - Quad. temp. dependence,
  - Field independent

Too weak/improbable

-Van Kranendonk, Walker, PRL, (1967)
Theory: Solid $^{129}$Xe Relaxation

- Direct processes less probable than two-phonon processes

![Graph showing density-of-states function for xenon at 10 K, normalized to unit area.]

FIG. 2. Density-of-states function for xenon at 10 K, normalized to unit area.

--Lurie, et al., PRB (1974)
Theory: Solid $^{129}$Xe Relaxation


\[
\frac{c_{K0}}{\hbar} = \left( \frac{\mu_K}{K \mu_B} \right) \left( \frac{\hbar}{8\pi M R_0^2} \right) (\sigma_g - \sigma_c)
\]

\[
\frac{c_{K0}}{\hbar} = -27 \text{ Hz}
\]

\[
\nu = \frac{c_K}{\hbar} K \cdot | \cdot \omega = c_K K \cdot N
\]
Theory: Solid $^{129}$Xe Relaxation

$-1R$, Fitzgerald et al., PRB (1999)

$\frac{1}{T_1^S} = \frac{9\hbar^2 \mu_K^2 (\sigma_g - \sigma_c)^2}{256\pi K^2 \mu_B^2 M^2 R_0^2 T_D^2} \sum_m g_m \left( 4 + \frac{8}{3} \epsilon_0 + \frac{1}{3} \epsilon_0^2 (2 \cos^2 \theta_m + 1) \right)$

$\times \int_0^1 du u^4 \frac{e^{uT_D}}{\left( e^{\frac{uT_D}{T}} - 1 \right)^2} \left[ 1 + \text{sinc} \left( u \sigma_m (6\pi^2 \sqrt{2})^{\frac{1}{3}} \right) + \text{sinc} \left( u (6\pi^2 \sqrt{2})^{\frac{1}{3}} \right) \right]^2$

$c_{K_0} = \left( \frac{\mu_K}{K \mu_B} \right) \left( \frac{\hbar}{8\pi NR_0^2} \right) (\sigma_g - \sigma_c)$

$c_{K_0} = -27 \text{ Hz}$

$\nu = \frac{c_K}{\hbar} K \cdot \boldsymbol{\omega} = c_K K \cdot \mathbf{N}$

$\epsilon = R \frac{d}{dR} \ln c_K$

<table>
<thead>
<tr>
<th>$m$</th>
<th>$g_m$</th>
<th>$\sigma_m$</th>
<th>$\cos(\theta_m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12</td>
<td>$\sqrt{0}$</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>48</td>
<td>$\sqrt{1}$</td>
<td>$1/2$</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>$\sqrt{2}$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>48</td>
<td>$\sqrt{3}$</td>
<td>$-1/2$</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>$\sqrt{4}$</td>
<td>-1</td>
</tr>
</tbody>
</table>
Theory: Solid $^{129}$Xe Relaxation


$$\frac{1}{T_1^S} = \sum_m g_m \left( 4 + \frac{8}{3} \epsilon_0 + \frac{1}{3} \epsilon_0^2 (2 \cos^2 \theta_m + 1) \right)$$

Conservation of momentum

Temperature dependence

$$\times \int_0^1 du \ u^4 \frac{u^{TD}}{e^{u^{TD}/T} - 1}$$

Spin-rotation coupling strength

$$\frac{c_{K0}}{\hbar} = -27 \text{ Hz}$$

Hanni, $c_{K0}/\hbar = -16 \text{ Hz}$
Theory: Solid $^{129}$Xe Relaxation

- Fermi’s golden rule

$$dW_{fi} = \frac{2\pi}{\hbar} |\nu_{fi}|^2 \rho(E_e) d\Omega_e$$

$$\nu = \sum_{\beta} c_K(R_{\beta\alpha}) N_{\beta\alpha} \cdot K$$

$$= \frac{1}{2\hbar} \sum_{\beta} c_K(R_{\beta\alpha}) R_{\beta\alpha} \times P_{\beta\alpha} \cdot K$$
Theory: Solid \(^{129}\text{Xe}\) Relaxation

- Fermi’s golden rule

\[
\begin{align*}
    dW_{fi} &= \frac{2\pi}{\hbar} |\nu_{fi}|^2 \rho(E_e) d\Omega_e \\
    \nu &= \sum_\beta c_K(R_{\beta\alpha}) N_{\beta\alpha} \cdot K \\
    &= \frac{1}{2\hbar} \sum_\beta c_K(R_{\beta\alpha}) \mathbf{R}_{\beta\alpha} \times \mathbf{P}_{\beta\alpha} \cdot K
\end{align*}
\]

- Initial and final states

\[
\begin{align*}
    |i\rangle &= |m_K = 1/2; \ldots, n_{k_{ja}a}, n_{k_{je}e}, \ldots\rangle, \\
    |f\rangle &= |m_K = -1/2; \ldots, n_{k_{ja}a} - 1, n_{k_{je}e} + 1, \ldots\rangle
\end{align*}
\]
Theory: Solid $^{129}\text{Xe}$ Relaxation

- Fermi’s golden rule
  
  \[ dW_{fi} = \frac{2\pi}{\hbar} |\nu_{fi}|^2 \rho(E_e) d\Omega_e \]

- Initial and final states
  \[ |i\rangle = |m_K = 1/2; \ldots, n_{k_{a_j}a}, n_{k_{e_j}e}, \ldots\rangle, \]
  \[ |f\rangle = |m_K = -1/2; \ldots, n_{k_{a_j}a} - 1, n_{k_{e_j}e} + 1, \ldots\rangle \]

- Canonical quantization
  \[ R_{\nu} = R_{\nu}^{(0)} + S_{\nu} \]
  
  \[ S_{\nu} = \sqrt{\frac{\hbar}{2NMc_s}} \sum_{kj} \frac{x_j}{\sqrt{k}} \left[ a_{kj} e^{ik \cdot R_{\nu}^{(0)}} + a_{kj}^\dagger e^{-ik \cdot R_{\nu}^{(0)}} \right] \]
  
  \[ P_{\nu} = \sqrt{\frac{\hbar Mc_s}{2N}} \sum_{kj} \sqrt{kx_j} \left[ ia_{kj}^\dagger e^{-ik \cdot R_{\nu}^{(0)}} - ia_{kj} e^{ik \cdot R_{\nu}^{(0)}} \right] \]
Theory: Solid $^{129}$Xe Relaxation

- At high temp., temp. dependence comes from only phonon occupation numbers, $n$

$$| \langle n_i - 1, n_j + 1 | a_i a_j^\dagger | n_i, n_j \rangle |^2 = n_i (n_j + 1)$$

Fermi’s golden rule

- These occupation numbers are averaged over using a Bose-Einstein distribution

$$< n_i > < n_j + 1 > = \frac{1}{e^{x/T} - 1} \frac{e^{x/T}}{e^{x/T} - 1}$$
Theory: Solid $^{129}$Xe Relaxation

Which appears exactly in $T_1$ formula

$$\frac{1}{T_1^S} = \frac{9 \hbar^2 \mu_K^2 (\sigma_g - \sigma_e)^2}{256 \pi K^2 \mu_B^2 M^2 R_0^2 T_D^2} \sum_m g_m \left( 4 + \frac{8}{3} \epsilon_0 + \frac{1}{3} \epsilon_0^2 (2 \cos^2 \theta_m + 1) \right)$$

$$\times \int_0^1 du \ u^4 \frac{e^{u T_D}}{e^{u T_D/T} - 1} \left[ 1 + \text{sinc} \left( u \sigma_m \left( 6 \pi^2 \sqrt{2} \right)^{1/3} \right) + \text{sinc} \left( u \left( 6 \pi^2 \sqrt{2} \right)^{1/3} \right) \right]^2$$

$$\langle n_i \rangle \langle n_j + 1 \rangle = \frac{1}{e^{x/T} - 1} \frac{e^{x/T}}{e^{x/T} - 1}$$
Theory: Solid $^{129}$Xe Relaxation

- At high temp. (higher than Debye temp., 55 K), each unique $n$ contributes $T$

\[
\langle n_i \rangle \langle n_j + 1 \rangle = \frac{1}{e^{x/T} - 1} \frac{e^{x/T}}{e^{x/T} - 1} \rightarrow \frac{1}{1 + x/T - 1} \frac{1}{1 + x/T - 1} \propto T \times T
\]
The third phonon’s occupation number in the aR process drops out, $T^2$ remains

\[< n_i > < n_j + 1 > = \frac{1}{e^{x/T} - 1} \frac{e^{x/T}}{e^{x/T} - 1} \]
\[\rightarrow \frac{1}{1 + x/T - 1} \frac{1}{1 + x/T - 1} \propto T * T\]
Theory: Solid $^{129}$Xe Relaxation

Irrespective of mechanism, any generic process has a temperature dependence defined by the number of unique external phonons.

\[ \langle n_1 \rangle \cdots \langle n_i \rangle \propto T^i \] (High-temp.)
Theory: Solid $^{129}$Xe Relaxation

- Though energy conservation is violated, consider non-unique phonon case

\[ | \langle n | a^\dagger a | n \rangle |^2 = n^2 \]

Fermi’s golden rule

\[ \langle n^2 \rangle = \langle n \rangle + 2 \langle n \rangle^2 \propto T + 2T^2 \]

(High-temp.)
Theory: Solid $^{129}$Xe Relaxation

- In scattering problems, conservation of momentum is more strict than energy.

$$ W_{fi} = \frac{2\pi}{\hbar} \sum_{j_e,j_a} \int_0^{E_D} dE_a d\Omega_a d\Omega_e |v_{fi}|^2 \rho^2(E_a) $$

- Typically in phonon scattering, a sum over entire lattice generates a delta function.

$$ \frac{1}{N} \sum_l e^{i r_l \cdot (k_1 - k_2)} = \Delta(k_1 - k_2) $$

$$ \Delta(k) = \begin{cases} 1 & \text{if } k = G, \\ 0 & \text{otherwise.} \end{cases} $$
Theory: Solid $^{129}\text{Xe}$ Relaxation

- Momentum conservation leads to a sizable difference

$T_1 = 300 \text{ min.}$

$T_1 = 1500 \text{ min.}$

(Using Hanni/$h$, $c_{k0} = -16 \text{ Hz}$)
Open: Solid $^{129}$Xe Relaxation

- Much future work, reopens field
- Create a structure-dependent theory
- Determine conservation of momentum
- Get lower temp. ice data, single crystal(?)
- Snow, experiments and theory
Finished: Solid $^{129}$Xe Relaxation

- Developed ice method that allows for unprecedented, robust $T_1$ data

- Discovered intrinsic difference between bulk snow and ice

- Found generic high-temp. $T_1$ behavior

- Found structural dependence in dilute $T_2$
Unconventional MR
Semiconductor ODMR/EDMR

- Optically Detected MR, Electrically Detected MR; dipolar and exchange

- Permutation symmetry of paramagnetic pairs determines signal, not polarization

\[ |\uparrow\uparrow\uparrow\rangle \]
\[ \cos(\phi) |\uparrow\downarrow\rangle - \sin(\phi) |\downarrow\uparrow\rangle \]
\[ \cos(\phi) |\uparrow\downarrow\rangle + \sin(\phi) |\downarrow\uparrow\rangle \]
\[ |\downarrow\downarrow\rangle \]
Resonate spin-1/2 pair, detect the optical or electrical deviation from steady state
Semiconductor ODMR/EDMR

- Repeat for detuned pulses
Semiconductor ODMR/EDMR

- Implemented Liouville-space formalism, allowing for quick computation of inhomogeneous, stochastic Liouville equation, for dipolar and exchange coupled pairs

\[ \rho = \begin{pmatrix} \langle \uparrow \mid \uparrow \rangle & \langle \downarrow \mid \downarrow \rangle \\ \langle \downarrow \mid \uparrow \rangle & \langle \downarrow \mid \downarrow \rangle \end{pmatrix} \begin{pmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{pmatrix} \]

\[ \rho = \begin{pmatrix} \rho_{11} \\ \rho_{12} \\ \rho_{21} \\ \rho_{22} \end{pmatrix} \]
Generation takes 10 min. instead of 7 days.

Limes, et al., PRB (2013)
Semiconductor ODMR/EDMR

- Showed that single-transition Rabi frequencies are given by

$$\Omega_{ij} = \sqrt{(1 \mp \sin 2\phi) (\gamma B_1)^2 + (\omega - \omega_{ij})^2}$$

and with sufficient dipolar coupling,

$$\sin 2\phi \to -1$$

leading to an on-resonant Rabi frequency

$$\sqrt{2\gamma B_1}$$
Mixed MR
Apply a $B_0$ modulation field, $B_2'$
$B_0$ modulation

- Readjust for comfort, quantization x’-axis
$B_0$ modulation

- Access unconventional regimes, $B_2 \gg B_1$

Relatively high polarization
$B_0$ modulation

- Determine Rabi envelope dynamics $B_1 \gg B_2$

\[ \omega_m \neq \Omega_R \]

RWA 2

RFBS

\[ \omega_m \neq \Omega_R \]

RWA 2

Rabi frame

$B_{Reff}$
$B_0$ modulation

- Regime: weak-resonant modulation

Glenn, Limes, et al., PRB (2013)
Overview

Magnetic Resonance

Conventional (NMR)
- Solid $^{129}$Xe Relaxation

Unconventional (ODMR/EDMR)
- Dipolar Coupling
  $\Omega_R = \sqrt{2}\Omega$

Mixed ($B_0$ modulation)
- Three regimes
- Rabi frame
Acknowledgements/Work
Acknowledgements / Heidi